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Model for the sigmoidal curvature of submarine slopes

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ABSTRACT

Sigmoidal slope profiles are common on the margins of continents and intracratonic basins. We propose that these profiles consist of two genetically different segments. The lower, concave part reflects the exponential decrease of the sedimentation rate with increasing distance from the source at the shelf edge. The upper, convex part represents the gradational boundary between the shelf domain where sediment is moved by waves (and wave-induced currents) and the slope domain where sediment is moved by gravity. The boundary is narrow and the shelf edge is sharp if sedimentary base level remains stationary during progradation; the boundary becomes gradational and the shelf edge becomes rounded if storms and sea-level cycles induce significant fluctuations of base level. This model is supported by observations on Holocene sedimentary systems as well as numerical simulations with the program STRATA based on the diffusion equation for sediment dispersal.

Keywords: slope sedimentation, shelf environment, modeling, sea level, seismic stratigraphy.

INTRODUCTION

The study of angle and curvature of submarine slopes has steadily gained momentum in the past decade, particularly because reflection seismic profiles provide a wealth of quantitative data on slopes, both in the modern oceans and in ancient sedimentary basins. The first-order morphology of the solid Earth is controlled by tectonic processes, and slopes are no exception to this rule. However, even on active ocean margins, sedimentary processes emerge as an important modifier of tectonic patterns (e.g., Gorsline, 1991). On passive margins or in cratonic basins, erosion, transport, and deposition rival the effects of tectonics. It is this second group that is the principal subject of this study.

The main motive for the study of depositional slopes is the desire to use their shape for prediction of sediment composition and slope stability. With regard to slope angle, it has been shown that the effect of grain size on the angle of repose of modern terrestrial slopes also applies to slopes in the geologic record (Kenter, 1990; Emery and Myers, 1996; Wright and Burchette, 1996). Quantitative analysis of slope curvature has received less attention. A pioneering study by Kenyon and Turcotte (1985) demonstrated the exponential curvature of certain delta slopes and related it to the exponential decay of creep and slumping with increasing distance from the sediment source at the shelf edge. Pirmez et al. (1998) modeled sigmoidal clinoforms in front of a river mouth, considering shear stress as the principal control of sediment dispersal. We pursued the diffusion-based approach of Kenyon and Turcotte (1985). Adams et al. (1998) showed that exponential curvature observed by Kenyon and Turcotte on prodelta slopes is common in the marine domain. In a survey of submarine slopes from all major oceans, 20% follow exponential curves that commence at sharp shelf breaks. These slopes have in common that the shelf break, i.e., the boundary between the domain of wave-controlled sediment transport and the deeper domain of gravity transport, fluctuated very little compared to the rate of horizontal progradation. Adams and Schlager (2000) took this line of reasoning a step further and speculated that sigmoidal slope profiles develop if the shelf edges are rounded off by large fluctuations of base level. The purpose of this paper is to test this concept by examining the anatomy of sigmoidal slopes and by simulating the effects of base-level fluctuations on the shelf break with a stratigraphic modeling program.

MODEL

We propose that sigmoidal shelf to basin profiles originate from the combined effects of base-level fluctuations at the shelf break and the exponential decay of gravity transport of sediment at the base of the slope.

Kenyon and Turcotte (1985) proposed that sediment transport by creep and slumping on prograding prodelta slopes can be modeled by a diffusion equation yielding slopes with exponential curvature. The equation has the form

$$\partial h/\partial t = -\mathrm{K} \times \partial^2 h/\partial x^2, \tag{1}$$

where $\partial h/\partial t$ is the rate of change of the sediment surface with time, $\partial^2 h/\partial x^2$ represents the change of the slope along the (downslope) profile, and K is the diffusion coefficient; it is negative because the elevation h decreases with increasing distance on the x axis. From a survey of submarine slopes in a variety of settings, Adams et al. (1998) concluded that the diffusion model might also apply to sediment dispersal by small turbidity currents. This inference is hydrodynamically plausible because the stream power of turbidity currents is a function of slope inclination (e.g., Allen, 1985).

In Kenyon and Turcotte's (1985) model, the shelf-slope break is sharp and marks the boundary between two very different regimes of sediment dispersal: on the shelf, sediment is transported very efficiently by waves and wave-related currents; on the slope, transport occurs less efficiently by gravity. The exponential curvature of the slope reflects the decay of gravity transport with increasing distance from the sediment source at the shelf break.

We propose that the sharp shelf break is not stable if depositional base level fluctuates under the influence of storms and changing sea level. Integrated over time, these fluctuations produce a rounded shelf edge. This process will happen wherever the rate of change in base level is significant compared with the rate of progradation of the shelf edge.

The model aims at first-order trends and accepts a number of simplifying assumptions. It is best suited for basin margins that are well supplied with sediment, where principal sediment transport is orthogonal to the strike of the slope, and grain-size variations are minor.

SUPPORTING FIELD EVIDENCE

The model is in agreement with observations on natural profiles, particularly if one systematically compares examples of exponential and sigmoidal curvature. In a global survey, Adams et al. (1998) found that all sharp-edged, purely exponential profiles were special in the sense that the rates and amplitudes of vertical fluctuations of base level were small compared to the rate of slope progradation. Sharp shelf edges and purely exponential curves were found on (1) reef-rimmed carbonate platforms where organic frame building and marine cementation create a rigid rim that resists erosion and reworking, (2) continental slopes having adjacent shelves that were ice covered in the recent past; and (3) deltas in Alpine lakes, where ample sediment supply leads to high rates of progradation while lake level is stable because the lake remains filled to spill point, and the effect of storms is minor because of small fetch.

It is important to note that the development of sigmoidal or sharp-edged exponential profiles is not simply a function of base-level fluctuations, but depends on the ratio of the rates of base-level fluctuation and progradation. This relationship is well illustrated by the Mississippi Delta, where sigmoidal and purely exponential profiles occur side by side (Fig. 1).

SUPPORT FROM STRATIGRAPHIC MODELING

We have used the stratigraphic modeling program STRATA to test the hypothesis that fluctuations of base level can round off shelf breaks and thus transform slope profiles with exponential curvature bounded by sharp shelf breaks into sigmoidal profiles.

The STRATA modeling program was introduced by Jordan and Flemings (1991) and Flemings and Grotzinger (1996). Based on few, but fundamental physical principles, it allows examination of the extent to which these principles can explain sedimentary architecture. The following program attributes are especially relevant for our experiments.

1. The cumulative effect of sedimentation and erosion over long time spans is described by the diffusion process as in equation 1.

2. The diffusion of sediment on land is more efficient (by two to four orders of magnitude in two-dimensional models) than in the deep-marine realm. The zone of shallow-water wave action is a region of transition where diffusion efficiency (as expressed by the diffusion coefficient, K) decreases exponentially with water depth, in response to the exponential decay of wave power (Allen, 1985; Kaufman et al., 1991; Flemings and Grotzinger, 1996). The diffusion coefficient in the transition zone from the terrestrial domain of high diffusivity to the deep-marine domain of low diffusivity is described by the equation

$$K = K_m + (K_n - K_m) \times e^{-\lambda d}, \qquad (2)$$

where K_m and K_n are the diffusion coefficients for the marine and nonmarine domains, λ is a decay constant that determines how rapidly the high diffusivity of the nonmarine domain approaches the low diffusivity of the deep-marine domain, and d is water depth.

3. The modeling operations honor the law of conservation of mass by conserving sediment volume (expressed as cross-sectional area in these two-dimensional models).

The STRATA runs used to test our conceptual model of sigmoidal clinoforms are summarized in Figure 2. The results apply to a wide range of numerical values in space, time, and space/time rates; furthermore, they apply equally well to siliciclastic systems with external sediment input and to carbonate systems with sediment production in the shallow-water domain.

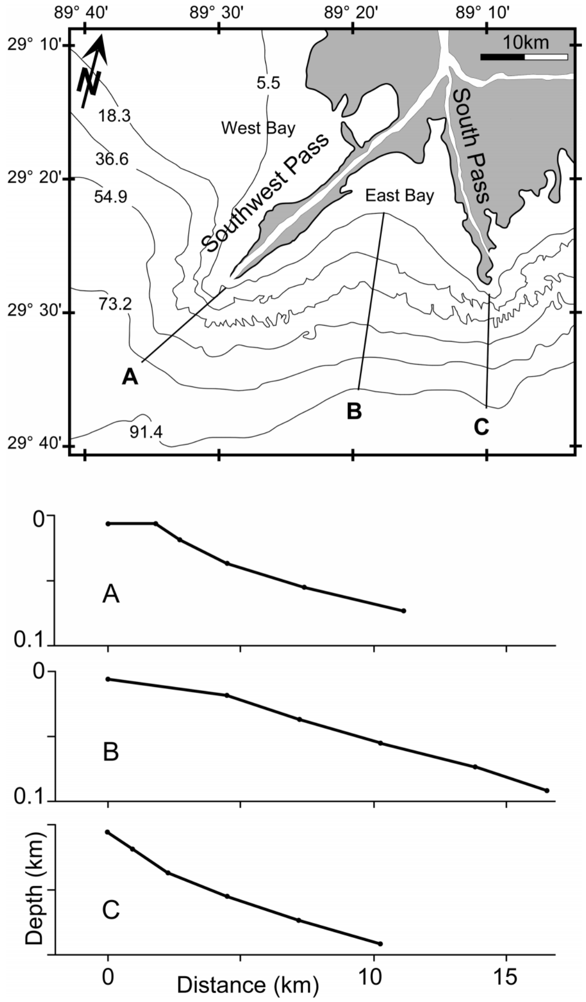

Figure 1. Profiles of Mississippi Delta based on Fisk et al. (1954). Top: Bird-foot anatomy leads to subdivision of delta front into areas of high sediment supply at mouths of distributary channels and intervening areas of lower supply that are currently stationary or erosional. Contour intervals are in meters. Bottom: Delta foreslopes of high-supply areas in front of Southwest Pass and South Pass are concave with sharp breaks at upper end. Slopes outside high-supply routes are distinctly convex in upper parts.

Figure 2 shows a siliciclastic shelf with sediment supply from the left, and K_n 666 times higher than K_m. The equilibrium condition of such a system is a flat shelf juxtaposed to a relatively steep slope with an exponential curvature. The geometry of the shelf break, the boundary between the high-diffusion and the low-diffusion domains, is a function of the thickness of the (shallow water) transition zone; this thickness is determined by the decay constant λ in equation 2. In Figure 2A, with $\lambda = 0.5$, the diffusion coefficient decreases from the nonmarine values to 105% of the marine value in the upper 19 m of the water column, and the shelf break is sharp. In Figure 2B, with $\lambda = 0.1$, the equivalent decrease in diffusion coefficient extends over 95 m of water column, and the resulting shelf profile is rounded and gradational. In nature, Figure 2A may represent a shelf subject to minor storm activity, whereas Figure 2B may represent a shelf with severe storms.

Figure 2C illustrates the effect of small sea-level fluctuations on the shelf system in Figure 2A. The shelf break becomes rounded under the influence of sinusoidal sea-level cycles of 10 m amplitude and

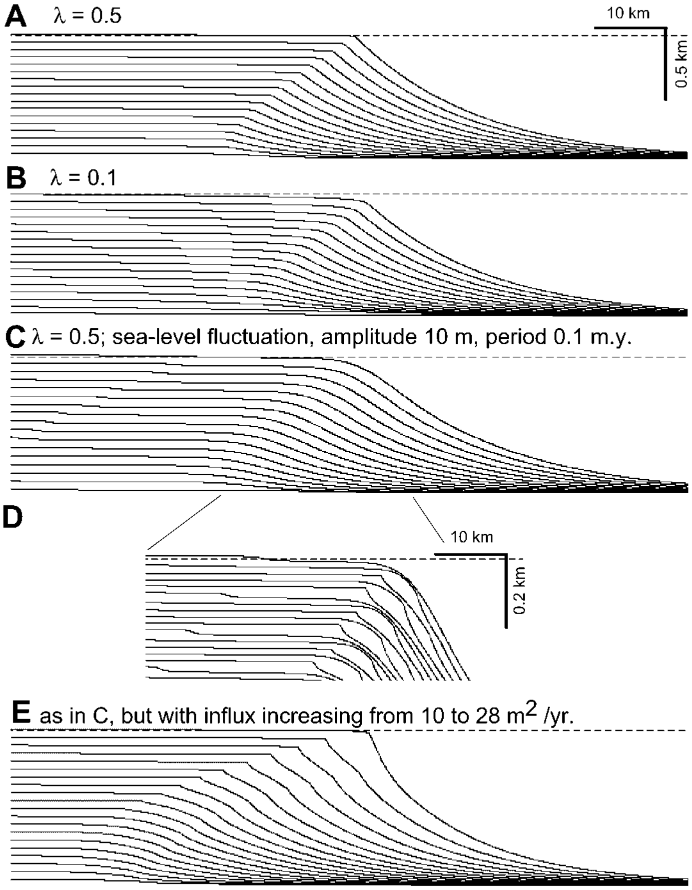

Figure 2. Two-dimensional simulations with program STRATA. Basic settings: Uniform subsidence of -1.67×10^{-4} m/yr; sediment supply from left starts at 10 m^2/yr, increasing with 2 m^2/yr·m.y.$^{-1}$; nonmarine diffusion coefficient $K_n = 1 \times 10^5$, marine diffusion coefficient K_m = 150. Duration of run is 5 m.y., spacing of time lines is 0.3 m.y. A: With diffusion decay constant λ = 0.5, vertical transition zone between nonmarine and marine diffusivity domains is ~20 m. Resulting shelf break is sharp and adjacent slope is concave with exponential curvature. B: With decay constant λ = 0.1, transition zone between nonmarine and marine diffusivity realms has been increased to ~100 m. This change is tantamount to widening depth range of storm action and short sea-level cycles. Resulting shelf break is gradational and overall slope profile has become sigmoid. C: Decay constant reset to λ = 0.5. Rounded shelf break and sigmoidal slope are now produced by small sea-level fluctuations. D: Controls as in C, but with vertical exaggeration of display and number of time lines doubled. Expanded display reveals that rounded shelf break in C is caused by combination of shelf breaks that are sharp but do not stack vertically, and by rounding of older shelf breaks by marine erosion. E: Settings as in C, but with sediment supply increasing from 10 to 28 m^2/yr. Increased supply overrides rounding effect of sea-level cycles and restores sharp shelf break and exponential slope curvature.

100 000 yr period. Figure 2D presents a close-up view. It shows that the rounding is accomplished by stepwise retreat of the shelf break during the phase of rapid sea-level rise and by rounding of the old, inactive shelf breaks by marine erosion. Figure 2E shows the system as in Figure 2C, except that now the sediment supply increases more rapidly and to higher values (28 m^2/yr compared to 14 m^2/yr in run C). With such high sediment supply the sharp shelf edge is restored despite the rounding effect of fluctuating sea level.

The features that produce the rounded shelf margins in the STRATA modeling runs when sea level is allowed to oscillate are commonly observed in nature. Rows of backstepping shelf breaks have been described in many areas that record the Holocene transgression (Hine and Neumann, 1977; Lighty et al., 1978; Kraft et al., 1987; Gensous et al., 1993; Thomas and Anderson, 1994; Goodbred et al., 1998). Similarly, geometric evidence for marine erosion on shelf edges has been observed repeatedly, and the patterns are remarkably similar to those generated by STRATA (e.g., Field et al., 1983). A plausible mechanism for marine erosion on high and distinctly convex structures is current reinforcement by topography-trapped waves (Schlager, 1999).

DISCUSSION

Our model depends critically on fluctuations of sedimentary base level. This was a fundamental difference to Pirmez et al. (1998), who produced sigmoidal clinoforms from shear-stress–dependent sediment dispersal in front of a river mouth. We believe that the frequent occurrence of sigmoidal slopes on carbonate platforms and open coasts argues against river discharge as a prerequisite of sigmoidal clinoforms.

Marine base level, i.e., the highest level to which marine sediment aggrades, is related to sea level, but not in a simple way. Sedimentologists traditionally distinguish between (1) fluctuations related to long-term changes in sea level and (2) wave-induced fluctuations related to atmospheric weather. We invoke both kinds to explain the rounding of shelf breaks and assume that the effects of both phenomena diminish with decreasing elevation. Storms may temporarily lower base level by 10^1–10^2 m, but only last for hours or days (10^{-4}–10^{-2} yr). Therefore, large depositional systems are affected by big storms but cannot equilibrate with the storm conditions. Thorne et al. (1991) argued convincingly that both the thickness distribution of storm layers and the amount of reworking, the quality most relevant for our problem, are governed by power laws such that events become rarer as they increase in intensity. This relationship implies that the effects of storms asymptotically approach zero as water depth increases and that there may be a significant zone of overlap between the wave-driven transport regime of shelves and the gravity-driven transport regime of the adjacent slopes. The STRATA program allows one to specify the thickness of this transition zone by changing the decay constant λ in equation 2.

Sea level fluctuates with a wide range of amplitudes and time scales. The growing demand for sea-level prediction on human time scales has produced a wealth of data on sea-level fluctuations at scales of 10^4–10^0 yr that are superimposed on the classical geologic cycles in the 10^5–10^8 yr domain (e.g., Sturges, 1990; Bloom and Yonekura, 1990). Generally, the amplitudes of sea-level cycles decrease with decreasing duration. As with storms, small-amplitude fluctuations are frequent, but large changes are rare. A consequence of this frequency distribution is that the cumulative effect of sea-level fluctuations gradually diminishes with decreasing elevation. Simulations with STRATA show that the cumulative effect of sea-level cycles that are too small to be resolved individually is to round off the shelf break. Sea-level cycles have a rounding effect on the shelf break that is similar to the effect of a storm-related increase of the thickness of the transition zone between nonmarine and marine diffusivity domains (Fig. 2, B and C).

Taken together, these observations suggest that the effects of weather-induced and sea-level–induced fluctuations of base level overlap in their spatial and temporal scales. Their cumulative signature on sediment architecture is a continuum, and their impact asymptotically approaches zero as one moves downward on a basin slope.

The lower, concave parts of sigmoidal slopes pose no special problems for our model. Curve-fitting and semilog plots readily show that the curvature obeys an exponential function. Exponentially curved lower slopes are one of the most common characteristics of subaquatic slopes (Adams and Schlager, 2000). We attribute them to exponential decay of sedimentation rates with increasing distance from the sediment source. In sigmoidal and exponential slopes, this sediment source is at the lower limit of the highly efficient transport regime of the shelf. On slopes with a linear upper part at the angle of repose, the sediment source for the concave segment is at the lower boundary of the linear part.

The exponential decay of sedimentation is probably caused by superposition of several effects. Kenyon and Turcotte (1985) attributed the exponential curvature of delta slopes to the effects of slumping, creep, and bioturbation on an inclined surface. Similarly, one can argue that the frictional loss of momentum of sediment avalanches at the bases of planar slopes at the angle of repose will produce an exponential decrease of sedimentation rate with distance from the base of the planar slope. The exponential decrease of thickness of turbidite beds in the direction of transport (Bursik and Woods, 2000) indicates that deposition from turbidity currents may also follow this rule. However, the model of exponential decay of turbidity-current sedimentation with distance does not apply to sloshing currents in silled basins (Allen, 1985). Accumulations of such ponded, basin-plain turbidites also deviate from the exponential slope model (Adams and Schlager, 2000).

The model of the slope sigmoid that emerges from our observations of real profiles, from the modeling runs, and from principles of sediment dispersal on shelves and slopes consists of two genetically different segments. Downslope, the profile asymptotically approaches the basin plain because of the exponential decay of transport capacity and competence of gravity-driven sediment flows and other mass movements. Upslope, depositional base level fluctuates at a wide range of scales in time and space; these fluctuations round off the shelf break and the profile asymptotically merges with the shelf surface. Despite this heterogeneity, the resulting sigmoid closely matches (one half of) a Gaussian bell curve (Adams and Schlager, 2000). This match is reasonable given the success of the diffusion equation in modeling sediment dispersal; the solutions to the diffusion equation commonly yield a Gaussian curve (e.g., Scheidegger, 1991, p. 124; Turcotte, 1992, p. 97).

CONCLUSION

Sigmoidal curves are the most common type of shelf to basin profiles. We explain them as the interplay of exponential decay of sediment transport with increasing distance from the source at the shelf and remodeling of the shelf break by storms and sea-level fluctuations. The model is in agreement with observations in modern oceans, numerical simulations based on the diffusion equation for sediment dispersal, and principles of sediment transport by waves and gravity.

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